Spectrally and Radiometrically Stable Wide-Band On Board Calibration Source for In-Flight Data Validation in Imaging Spectroscopy Applications

J. B. Coles, Brandon S. Richardson, Michael L. Eastwood, Charles M. Sarture, Gregory R. Quetin, Marco A. Hernandez, Linley A. Kroll, Scott H. Nolte, Michael D. Porter, Robert O. Green

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91101
818-354-5759
coles@jpl.nasa.gov

Abstract— The quality of the quantitative spectral data collected by an imaging spectrometer instrument is critically dependent upon the accuracy of the spectral and radiometric calibration of the system. In order for the collected spectra to be scientifically useful, the calibration of the instrument must be precisely known not only prior to but during data collection. Thus, in addition to a rigorous in-lab calibration procedure, the airborne instruments designed and built by the NASA/JPL Imaging Spectroscopy Group incorporate an on board calibrator (OBC) system with the instrument to provide auxiliary in-use system calibration data. The output of the OBC source illuminates a target panel on the backside of the foreoptics shutter both pre and post data collection. The OBC and in-lab calibration data sets are then used to validate and post-process the collected spectral image data. The resulting accuracy of the spectrometer output data is therefore integrally dependent upon the stability of the OBC source. In this paper we describe the design and application of the latest iteration of this novel device developed at NASA/JPL which integrates a halogen-cycle source with a precisely designed fiber coupling system and a fiber-based intensity monitoring feedback loop. The OBC source in this Airborne Testbed Spectrometer was run over a period of 15 hours while both the radiometric and spectral stabilities of the output were measured and demonstrated stability to within <1%.

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1. INTRODUCTION

The airborne imaging spectrometer instruments developed by the NASA/JPL Imaging Spectroscopy Group are sensors designed to collect high spectral and spatial resolution image data across bandwidths typically ranging from 380nm - 2500nm. The quality of the image datasets collected is defined by the quantitative accuracy of the final data product. The process of applying a calibration adjustment to the data then necessarily imposes a limit on the ultimate quality of the dataset. For this reason, the imaging spectrometers undergo a rigorous calibration procedure developed at NASA/JPL to precisely characterize the performance of the instrument in the lab prior to delivery. This calibration is then applied to the collected data to produce the highly accurate final data product desired by many NASA/JPL customers. [1]

A demonstrated improvement to the system calibration process, the on board calibrator (OBC) has substantially increased the overall accuracy of the instrument image data products of the instruments. First, while the in-lab calibration of the instrument is performed, a set of measurements is made using the OBC as an illumination source on a calibration target. Then, while in flight, the OBC again illuminates the same calibration target in the spectrometer to measure calibration data both pre and post dataset collection. Using this in-flight calibration data the changes in the imaging spectrometer system characteristics that occur between the lab calibration and the collection of the specific dataset of interest can be recorded and factored into the final data processing. This supplementary calibration dataset thus serves to more accurately define the reference levels of each of the spectrometer channels, resulting in greater absolute and spectral accuracy of the final product. Assuming an accurate implementation of the calibration adjustment algorithm, the role of limiting factor for data quality thus shifts to the stability of the OBC source.

In this paper we outline and discuss the most recent advances in OBC system design. Specifically, the verification process of the spectral and radiometric stabilities of the OBC system implemented in the Airbone Testbed Spectrometer is presented and the results are quantified and analyzed to demonstrate the effectiveness of the new design. Finally, we summarize the advances made, the implications on future imaging spectrometers, and possible future directions for greater calibration improvement.

2. Traditional Operation of the OBC

Fundamentally, the OBC system is an extremely radiometrically and spectrally stable halogen-cycle illumination source. The radiometric stability of the source refers to the absolute intensity stability of radiation output across the entire band of interest, 380nm - 2500nm in this instance. Spectral stability, instead refers to the component wavelength relative stabilities across the bandwidth of interest. Together, these two stability metrics provide a measure of the spectroradiometric stability which corresponds to the measurements taken by the imaging spectrometers.

Current implementations of the OBC source integrate a medical/scientific grade halogen-cycle bulb with a precision machined FeNi36 (Invar) mounting body or housing. Coupling optics are securely mounted in the housing to guide the light produced from the bulb to the input face of the output fiber bundle filling the fiber acceptance angle. The fiber bundle then guides the generated light into the instrument and projects it onto the calibration target on the backside of the fore-optics shutter as needed.

Source Bulb Stability

The output of the OBC is precisely controlled by a feedback control circuit. In the earliest implementations, this was achieved via a constant current feedback system providing a precise power to the bulb over a given lifetime [2]. More recent versions of OBCs incorporate a constant intensity feedback loop using a secondary pickoff detector [3] monitoring bulb output. In this configuration, a small mirror is mounted to a standard silica window at a 45^{o} incident angle to the source beam in line with the optical path in order to image the bulb filament onto the detector. The voltage output generated by the pickoff detector in response to the illumination is then fed into the input of the feedback circuit. The feedback circuit then adjusts amount of current delivered to the bulb accordingly to hold the detector output constant at the desired value. By controlling for the actual output intensity of the bulb rather than simply the power delivered to the bulb, the effects of the filament degradation, warm up and other variables which influence the efficiency of the light output on the system stability are significantly diminished.

Thermal Variation Mitigation

A primary source of instability in the OBC source output is the thermal variation of the system [3]. The silica optics of the OBC are secured in the Invar housing using Invar rings to match coefficients of thermal expansion (CTE) as closely as possible. Additionally, the use of Invar as a housing material provides minimal thermal expansion of the overall optical path length (OPL), ensuring constant illumination of the fiber bundle face. A system of carefully placed polyimide heaters and thermocouples controlled by a thermal control unit serves to further isolate the OBC system from thermal variation by maintaining a system temperature above ambient.

3. OBC System Advances

The original implementations of OBC systems have effectively demonstrated the successful application of the concept of in-flight calibration data, however significant advances have recently been incorporated into OBC design that markedly improve the output stability of the system.

Feedback Circuit

Previous implementations of the OBC feedback circuit have traditionally incorporated both constant current and constant intensity feedback control of the OBC bulb as previously described. While the systems have been demonstrated to provide a suitable level of stability [4] the complexity of the resulting systems used made it difficult to adapt the design to interface with multiple systems. By changing the feedback circuit to control the voltage across the bulb rather than the current delivered to the bulb based on the input of the intensity seen at the pickoff detector multiple stages of circuitry are eliminated and the circuit loses levels of complexity. Technologically, advances in operational amplifier (op-amp) technology have allowed for greater precision op-amps to be used in the comparator circuit. This additional precision thus leads to less feedback noise and greater potential output intensity stability.

Level Switching

In traditional operation, the OBC source outputs a single calibration light level throughout the entire flight time with OBC calibration data collected at the beginning and end of each data set collection. In this mode of operation, the OBC bulb is then continuously running at standard operating power to maintain halogen cycle stability. Collecting calibration data in this manner allows for accurate real time monitoring of the imaging spectrometer instrument while in flight, generating a quantitative measure of the stability of the calibration of the system.

The halogen bulbs that are used in OBC systems combined with the attenuation coefficients of the optics and the silica of the fibers used result in a significantly lower output power at short wavelengths as compared to infrared (IR) wavelengths (Figure 1). Such a weak signal results in reduced signal to noise ratios (SNR) in the dataset.

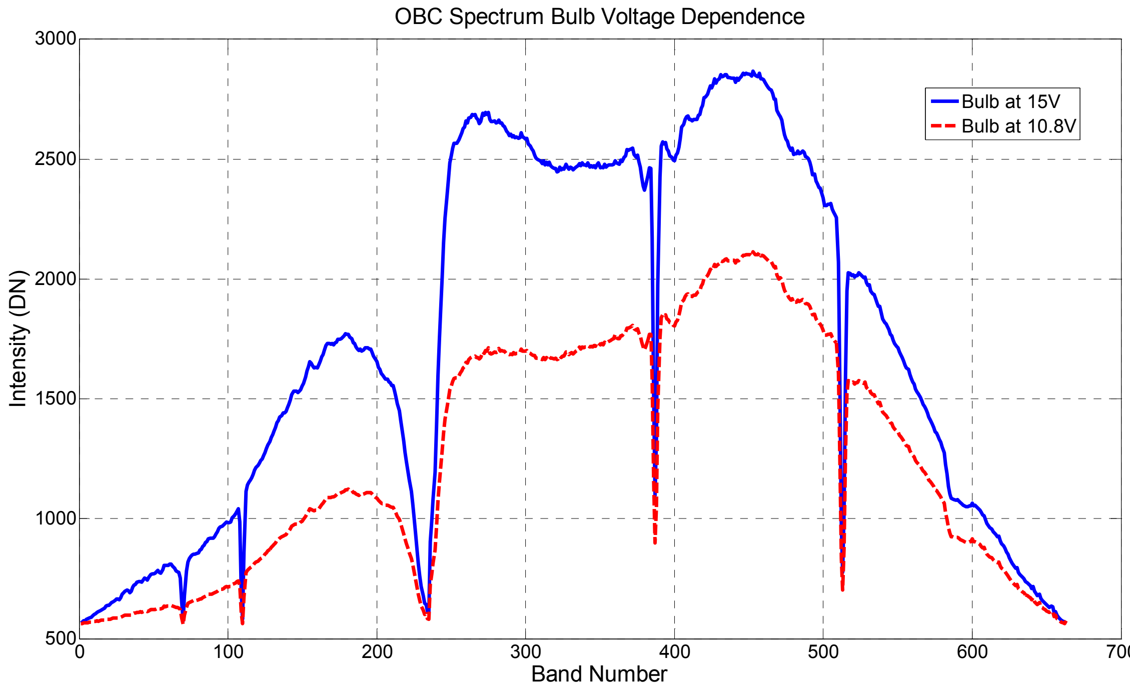

Figure 1 - OBC two-level output spectrum as measured by the Airborne Testbed Spectrometer

In order to more carefully monitor system performance in the short visible wavelength region a new method of operation concerning output levels has been introduced to the system. When a halogen bulb is run at an operating power greater than that specified by the manufacturer (overrating), the output spectrum experiences a shift similar to the shift induced by the temperature change of a standard black body emitter. As such, the level of the short wavelength visible light is increased by an amount proportional to the power increase delivered to the bulb. By running the source at a level of 150% of the manufacturer specified operating power, termed high level, the intensity throughput of the system at short wavelengths can be increased to a level appropriate for system calibration as shown in Figure 1.

While increasing the operating power of the bulb is an obvious solution to the attenuation of the visible blue wavelengths in the OBC, the operational lifetime of the halogen bulb is exponentially diminished from overrating due to undue stress on the bulb filament. Thus, the choice of an operating point 150% greater than the manufacturer specification would result in a significant loss of bulb lifetime. A shorter bulb lifetime would then compound further on the maintenance issues that premature bulb failures have caused in previous applications [3] requiring a significant increase in maintenance time. In order to compensate for this additional wear on the bulb filament, another level of OBC operation, termed idle level, was introduced. By substantially decreasing the power applied to the bulb (derating) while calibration data is not being actively collected, the penalty incurred by running at the increased power to amplify the visible blue wavelengths is practically negated.

One caveat to the selection of the idle level is the desire to maintain a steady halogen cycle operation of the bulb. This requirement stems from the fact that there is a finite response time between the application of power and the output of the halogen bulb. This warm up time is drastically increased in the case of turning on a cold filament as opposed to one currently operating in the halogen cycle. If the power applied to the bulb crosses below the given threshold of the filament, the halogen cycle will cease and the filament will cool. The idle level must therefore be chosen sufficiently above the filament threshold such that the halogen cycle can continue to steadily operate, minimize the warm up time and preserve the stability of the system.

Thermal Control

As described previously, the thermal variation of the OBC system is the fundamental source of output instability [3]. While the use of an Invar housing and a well designed thermal control system significantly reduce the effect of thermal variations on the output of the system due to thermal expansion, this does not directly address the thermal drift of the feedback sensor. It is well known that the output of a silicon photodiode is strongly dependent upon temperature due to the change in the rate of carrier generation. This thermal dependence means that the output of the pickoff detector will follow the temperature variations of the system. This variation will then be fed into the feedback system and the control circuit will adjust the output power in response to the temperature change rather than actual output power change. Therefore if the pickoff detector is not closely thermally controlled, it will limit the overall system stability.

Simply expanding the thermal control system to include polyimide heaters on the pickoff detector is only a marginally adequate solution. The thermal mass of the Invar housing is so large that it induces a slow drift in the temperature of the detector which is too slow for typical thermocontrollers to compensate for sufficiently. Instead, the detector must be isolated from the Invar housing while staying in line with the pickoff mirror. This is accomplished using several Micarta FR4 grade laminate (G10) standoffs placed between the detector mount and the Invar housing. The non-conductive property of the G10 is sufficient to thermally isolate the detector from the housing with only about 1.5".

As an additional measure, the light imaged onto the pickoff detector is also filtered by a narrowband bandpass filter. The center wavelength of the filter is selected such that the passband falls within the region of minimum thermal dependence for the detector according to manufacturer specifications.

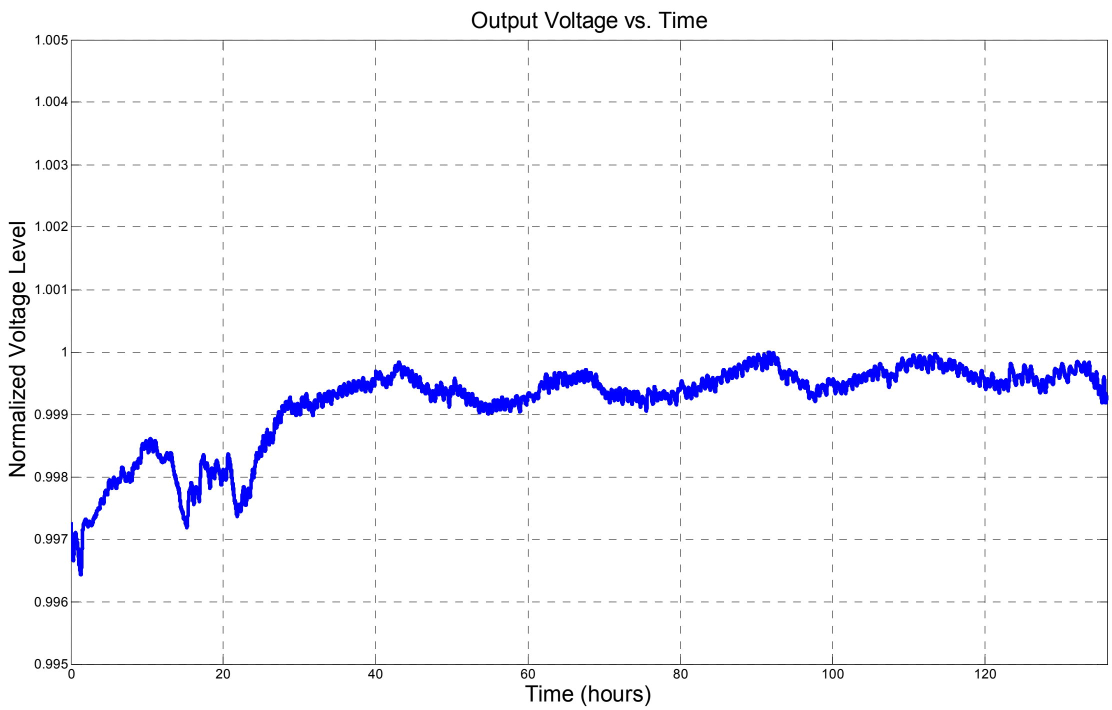

Figure 2 - Output voltage of silicon photodetector illuminated by the OBC system output over 136 hours.

Fiber Bundle

Another effective method of thermally isolating the pickoff detector is to move the detector from the housing entirely. In this configuration an additional tap fiber was added to the fiber bundle. The tap fiber consists of a random selection of approximately 5% of the total fiber bundle input face. By routing the tap to a point physically separated from the significant heat sources of the halogen bulb and housing thermal control system, the pickoff detector is able to be precisely temperature controlled by its own, independent, thermal control system. This method avoids the use of G10 standoffs while providing full thermal isolation.

By changing the stage that the light is fed to the feedback detector, the accuracy of the feedback control circuit is also increased. While the pickoff detector is an effective method for imaging a sample of the intensity emitted from the bulb, it fails to be an accurate representation of the actual system output. The pickoff mirror was necessarily placed at a point in the system prior to the final fiber coupling at the output. This limitation would result in invalid feedback data if anything downstream of the pickoff mirror were to experience a change. Using the signal from the tap fibers for the feedback detector instead allows the system to be controlled based on the actual output intensity coupled into the fiber bundle from the OBC source.

4. EXPERIMENTAL STABILITY VERIFICATION

The previously described system modifications were implemented as outlined in the Airborne Testbed Spectrometer OBC system. The system was configured and tested for spectral and radiometric stability in the laboratory at the Jet Propulsion Laboratory.

Radiometric Stability

The absolute radiometric stability over the entire band of interest of the proposed OBC system was tested on the laboratory testbed setup. An unused bulb was placed into the OBC housing and the OBC output fiber bundle was connected to an external silicon photodetector. The photodetector output current was converted to a voltage by a transimpedance amplifier box which output the voltage to a high resolution digital multimeter (DMM). The feedback system and thermal control system electronics were probed and monitored by a 10-channel data acquisition (DAQ) system to ensure proper system functionality and health. To provide proper thermal isolation from the temperature variations in the laboratory over the extensive testing period, the entire system was covered by a thick mylar thermal blanket and insulating foam. The output and tap fiber bundles were secured to the testbench in order to prevent any unexpected fiber bends. Finally, the data was collected by a computer script at a rate of one sample per second over a testing period of 136 continuous hours to ensure a thorough test dataset.

The data from the 136 hour test is depicted in Figure 2. The graph plots the normalized voltage output measured by the DMM against the time elapsed in the test in hours. The data clearly shows that the new OBC design is radiometrically stable to within 0.4%. The signal noise associated with such a level of stability is negligible compared to the signal chain and photon noise associated with the detectors typically used in imaging spectrometers.

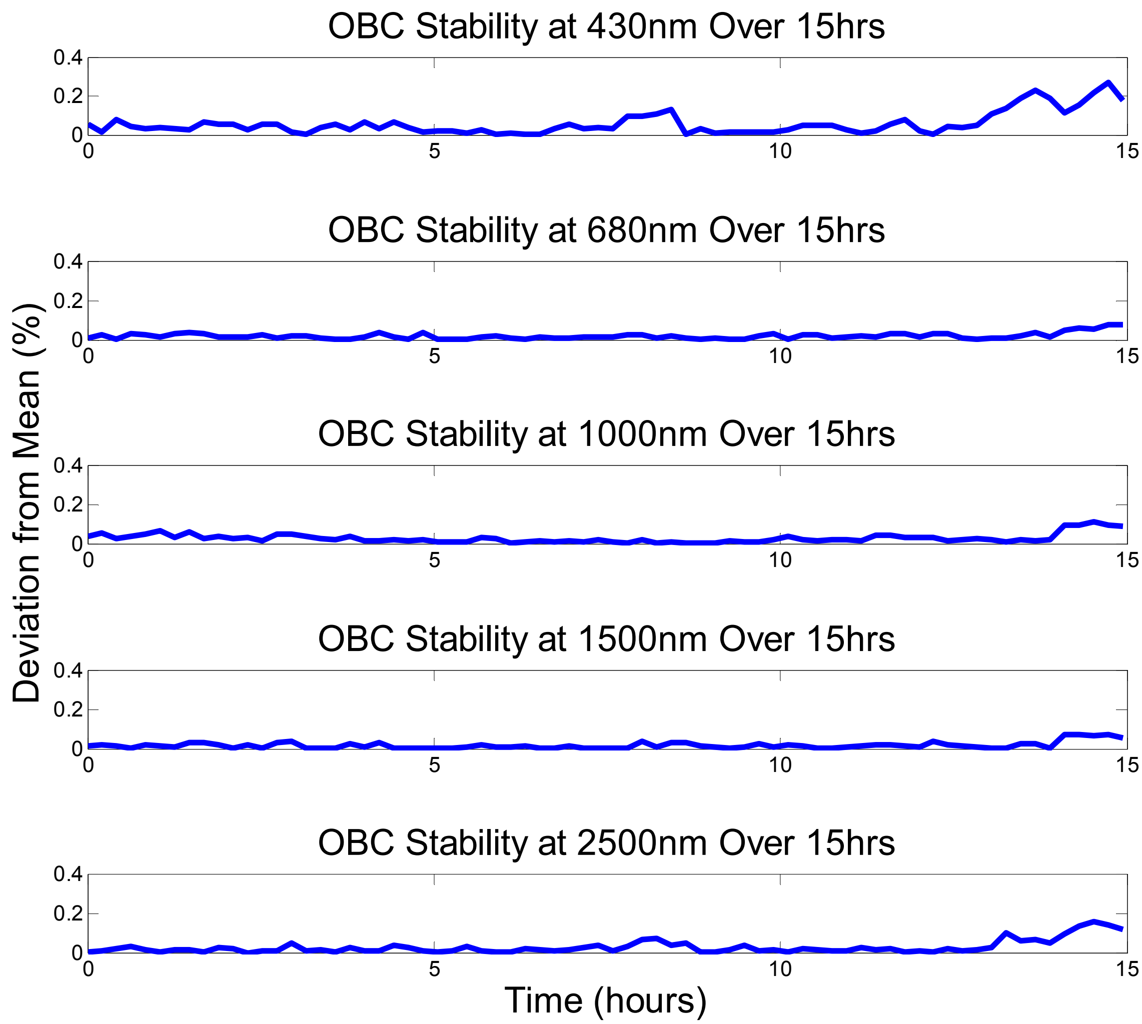

Figure 3 - The stability plots of five sample bands of the OBC output spectrum over a 15 hour test as measured by the Airborne Testbed Spectrometer. Wavelength samples are: 430nm, 2200nm, 680nm, 1000nm, and 1500nm. Percent deviations are found in Table 1.

It is also important to notice the warm-up period experienced for the first 30 hours. Given the bulb lifetime of 5000 hours, this break-in time is not a large concern. This region of operation is the only region demonstrating instability beyond 0.1%. The gradual increase in the output intensity can be attributed to the use of a new bulb in the system and the time it takes to prepare the brand new filament for stable illumination. While operation in this period presents a substantial stability penalty, the overall system instability is still negligible and therefore not a concern for current practical applications.

Spectral Stability

Spectroradiometric measurements such as those taken by the Airborne Testbed Spectrometer involve precisely calibrated radiation level detection within well defined spectral bands. If the OBC system is to be used as an in-flight calibration source for imaging spectrometer systems, then the spectral stability of the source is equally as important as the absolute radiometric stability. The spectral stability was measured by testing the spectroradiometric stability of the system in a similar manner to the radiometric stability setup. Instead of an intensity detector, the output collected spectral data over the course of a 15 hour test with samples collected every minute. The data was then exported and processed to measure the stability of each spectral band of the instrument under test. A sample of the radiometric stabilities within five representative bands is shown in Figure 3. It is important to note that none of the listed bands overlaps with the feedback detector filter passband.

As shown in Figure 3 and demonstrated in Table 1, the maximum spectroradiometric variation over the 15 hour period was 0.45% at 430nm with a minimum variation of 0.15% at 1.5um. As expected, the spectral bands with the least incident signal power from Figure 1 demonstrated the least stability. The data also shows that while the source is less stable spectrally than radiometrically across the bandwidth of interest, the noise produced by such a result would be negligible compared to other noise sources. This is a significant result in that it validates the assumption that the designed OBC source can be used as both a radiometric and spectral calibration source for high resolution imaging spectrometers.

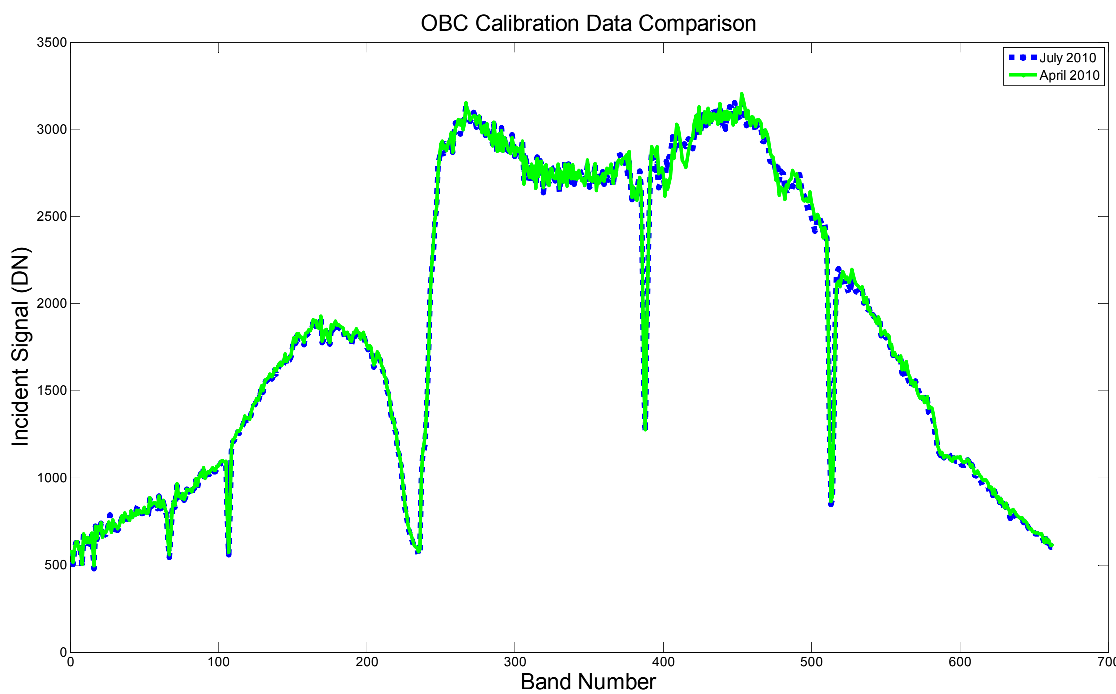

Figure 4 - Airborne Testbed Spectrometer OBC calibration data from April 2010 (green) and July 2010 (blue)

fiber bundle was fully integrated into the Airborne Testbed Spectrometer system as it would be in flight. The system feedback and thermal control electronics were monitored by the testbed system computer probing a DAQ. The system was encased in a steel box to completely isolate it from any external stimuli found in the laboratory environment and the fiber bundles were secured to the instrument rack to prevent unwanted fiber bends. The testbed system computer

Field Testing

As a final phase of testing, the OBC designed for use with the Airborne Testbed Spectrometer was also deployed to the field and used in data collection over the 2010 flight season. OBC calibration data was taken during every data run of the season and used to calibrate the collected image data. Figure 4 compares an OBC calibration spectrum taken during a calibration flight at the beginning of the flight season in April 2010 (green) and an OBC calibration spectrum taken three months later in July 2010 (blue). The data demonstrates a change on the order of 2.5% on average across the detector and up to 8% at maximum. Based on the laboratory characterization previously described, this spectral variation in can be attributed to a change in the response of the spectrometer instrument. This shift will be accounted for in the final processing of the image data based on the change of the OBC spectrum from the laboratory calibration to the field calibration samples. This temporal change in the instrument response demonstrates clear experimental evidence validating the need for an OBC source in airborne imaging spectrometer instruments.

5. Summary and Conclusion

We have presented a drastic improvement on a novel device developed specifically for use with highly accurate imaging spectroscopy systems. The usefulness of the final data product generated by an imaging spectrometer relies on the accuracy of the data produced. One fundamental way to ensure as high accuracy as possible is through a rigorous calibration procedure. In addition to an extremely accurate in-lab calibration method, the imaging spectrometers developed by the imaging spectroscopy group at NASA/JPL incorporate on board calibrators to provide supplementary calibration data. The OBC system was developed as a means of measuring the change in an imaging spectrometer's spectral and radiometric calibration over time while collecting data. The OBC calibration data can then be used to process the final data product output from the imaging spectrometer instrument in order to produce a more accurate dataset. In order for the OBC data to be useful for this purpose, however, the radiometric and spectral stabilities of the OBC system output must be ensured.

In this study we have proposed and demonstrated a number of OBC design improvements that were implemented and tested using the Airborne Testbed Spectrometer. The feedback circuitry was completely redesigned to incorporate voltage control feedback based on the output from a pickoff detector. The new circuitry also provides additional functionality to switch the power applied to the OBC bulb to different levels as appropriate. It produces a high intensity output for measuring visible blue levels, a mid intensity output for measuring calibration spectra as before, and an idle intensity level implemented to preserve bulb life and limit instrument maintenance time and costs. The pickoff detector was isolated from the OBC Invar housing to be thermally controlled independently and provide more accurate feedback levels for the control circuit. Finally, a 5% tap fiber set was included in the output fiber bundle to completely thermally isolate the feedback detector from the rest of the OBC system as well as to more accurately sample the OBC output in the feedback loop.

The radiometric and spectral stabilities of the proposed OBC design were measured in the laboratory. The measured absolute radiometric stability was measured to be stable to within 0.4% including bulb break in time which accounts for approximately 0.6% of the entire bulb lifetime. Following break-in, the OBC source demonstrated absolute radiometric stability to within 0.1%. The spectroradiometric stabilities of five sample bands representing the full spectrum of interest were also presented. The sample data demonstrated the spectroradiometric stability of the OBC source at to be stable to 0.45% in the 480nm band in the worst case and stable to 0.15% in the 1.5um band in the best case. The noise imparted on the final image data due to such small instabilities is negligible relative to other noise sources in the imaging spectrometer systems such and thus is not a concern.

Finally, the application and stability of the OBC calibration data was also demonstrated in the field over a three month period of flight comparing datasets from both the beginning and end of the flight season. The data demonstrated substantial variation compared to the in lab OBC calibration, demonstrating the potential usefulness of an OBC system for airborne imaging spectrometer instrument data analysis. Overall, the improvements to the overall stability of the OBC system justify the design changes and demonstrate the usefulness of the OBC as a calibration source for in flight measurements.

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BIOGRAPHY

James Coles *is currently an Electronics Engineer at the Jet Propulsion Laboratory in Pasadena, California working in the Imaging Spectroscopy group of the Instrument Systems section. Previous research endeavors have included extensive research in fiber optic parametric amplifiers and their applications in the telecommunications field, particularly in the arenas of Fiber Optic Parametric Amplifiers with Two Pumps and Stimulated Brillouin Scattering Suppression for high power amplification. He has a BSEE with an emphasis in Photonics and a MSEE in Applied Optics both from the University of California, San Diego.*